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Plastic Fins for Kinetic Energy (KE) Penetrators

by Mark L. Bundy

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Plastic Fins for Kinetic Energy (KE) Penetrators

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Abstract

Most conventional sub-caliber long rod penetrators maintain flight stability by using near-full-caliber hardcoated aluminum fins that extend from the base end of the projectile. Prior to launch, these fins are buried within the propellant bed of the ammunition cartridge case. During launch, the fins are subjected to high propellant gas temperature and pressure, as well as propellant grain impacts. This thermally abrasive in-bore environment can remove pieces of the fin's hardcoat, thus exposing the aluminum substrate to temperatures far beyond its melting point. Thermal erosion of the fin degrades projectile stability and accuracy. Thus, the U.S. Army is exploring more effective thermal coatings and/or substitute fin materials to replace hardcoated aluminum. The use of plastics is one alternative. This report will document some of the successes and failures of plastic fin assemblies on kinetic energy (KE) penetrators. For example, it was found that fins made from some plastics incur less in-bore thermal damage than hardcoated aluminum. On the other hand, it appears that plastic fins, at least relatively thin plastic fins, are susceptible to mechanical failure out of bore if they traverse the reverse muzzle gas flow at all but small yaw angles. Nonetheless, there appears to be design latitude for a plastic fin assembly that would be lighter in weight and more erosion resistant than the current hardcoated aluminum fin.

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1. INTRODUCTION

Unlike full-caliber projectiles that deliver high explosives to the target, sub-caliber long rod projectiles utilize kinetic energy (KE) to impart damage to the target. The more aligned the rod axis is with its velocity vector, the further it will penetrate into the target armor. Hence, stabilizing the penetrator to favor a minimum yaw angle is an important factor in defeating the enemy.

Most KE penetrators maintain flight stability by using near-full-caliber fins that extend from the base end of the projectile. The most common KE fin material is aluminum. A typical aluminum fin thickness for a U.S. Army tank main gun (e.g., 105-mm or 120-mm bore diameter) is about 2–3 mm. The standard aluminum fin is chemically treated to create a 0.05–0.08-mm aluminum oxide (refractory) surface layer (hardcoat), which provides considerable, but not complete, protection from thermal erosion.

Prior to launch, KE fins are buried within the propellant bed of the ammunition cartridge case. After propellant ignition, but before muzzle exit, the fins are exposed to high propellant gas temperature and pressure as well as propellant grain impacts. The relative motion between the propellant grains and the fin creates a thermally abrasive in-bore environment that can remove pieces of the hardcoat. Once the hardcoat has been removed, a series of in-bore events can produce rapid erosion of the exposed aluminum substrate. Bundy, Horst, and Robbins (1990) found evidence that where the hardcoat had been chipped away, heating from propellant combustion appeared to have raised the surface temperature of the underlying aluminum to its boiling point. It was then possible for evaporation and subsequent combustion of aluminum vapor to feed energy back to the surface, thus accelerating the "burning" process in width and depth along the fin. In fact, aluminum fin blades that were left uncoated were entirely consumed in a matter of milliseconds when the fin assembly was held at the end of the igniter tube (in close proximity to its initial position in a normal launch) during propellant combustion.

Furthermore, where in-bore erosion has taken place, the aluminum fin is left vulnerable to additional out-of-bore erosion from aerodynamic heating as it travels downrange, particularly for high velocity, long time-of-flight rounds. Not only will the loss of fin surface area reduce stability, it will reduce accuracy because it does not occur symmetrically on each fin blade.

To prevent the erosion of fin surface area, the U.S. Army has been exploring the use of thermal coatings (e.g. Garner 1996) and substitute fin materials, such as steel, to augment or replace hardcoated aluminum. Although an all-steel fin assembly will not incur in-bore damage (Bundy, Horst and Robbins 1990), the weight penalty for replacing aluminum with steel is a notable disadvantage. A compromise solution, examined here, is to use a steel fin in a lightweight plastic fin hub. However, the primary focus of this report is to examine all-plastic fin alternatives.

In spite of plastic's low melting temperature, it is a reasonable material for fin applications because the in-bore heating time is so brief, and the thermal conductivity is so low that only a thin layer of plastic is eroded while it is in bore. Furthermore, unlike aluminum, when plastic burns in bore, the energy released does not add significantly to subsequent fin surface heating. However, as the test results will show, thermal loads are not the only concern with an all-plastic, steel-in-plastic, or fiber-in-plastic fin assembly. If the projectile exits the muzzle at a nonzero yaw angle with respect to the reverse muzzle gas flow (as is common), the fins will encounter asymmetric dynamic pressure loads. The strength and toughness of plastics is then an issue as to whether or not the part will fail in its transition to free flight. The results presented here document some of the successes and failures, both thermally and mechanically, of plastic fins on long rod penetrators.

2. TEST AND EVALUATION PROCESS

2.1 Static Firing

Candidate fin assemblies were tested by attaching them to the end of a standard (bayonet-type) igniter tube extending from a 120-mm combustible cartridge case (stub) base, Figure 1. In this configuration,

the fin assembly remains in the gun chamber during and after the firing event. Normal (automatic) ejection of the stub base after firing is replaced by manual ejection, to reduce the risk of accidentally damaging the test fin during extraction from the gun chamber. As indicated, essentially all of the propellant (in either gas or solid phase form) must pass by the stationary fin assembly in the leading-to-trailing edge direction. The fins are thus exposed to more of the abrasive action of the two-phase (propellant gas and solid grain) flow than they would be if they were attached to the end of the projectile, moving down-bore along with the propellant. Nevertheless, subjecting the fins to thermal conditions that are more extreme than those incurred in a conventional launch provides a rigorous test for evaluating the in-bore success or failure of candidate fin coatings and materials.

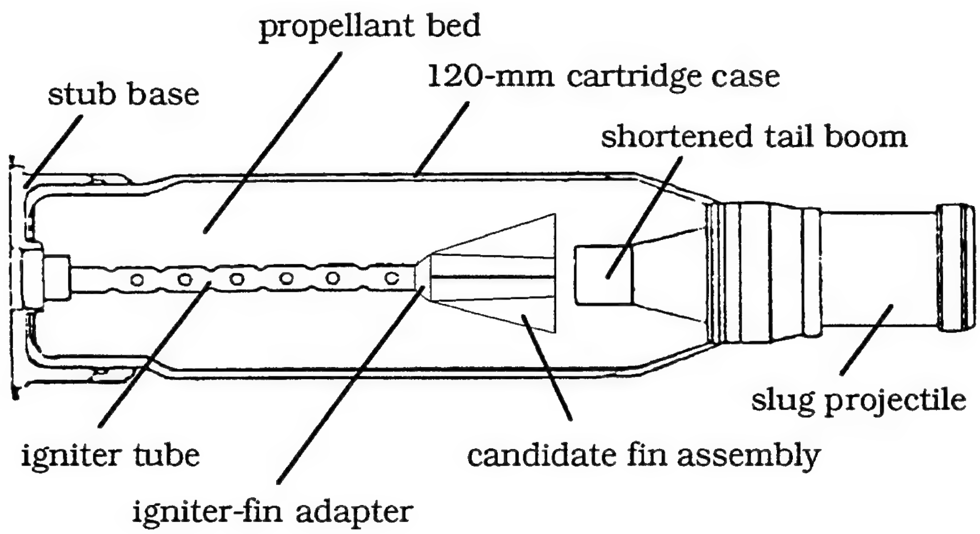


Figure 1. Experimental setup for testing candidate fin assemblies.

The projectile fired in the static fin test configuration is a standard slug round with a portion of its tail boom removed to provide space for the fin assembly attached to the end of the primer tube.* The propellant used was granular JA2; the amount was determined from interior ballistics modeling to be that needed to launch the modified slug at the

* Note, after launch, the flight performance of the slug, with its shortened tail boom, is not of interest.

same muzzle velocity as a standard M829A1 120-mm projectile.* Inspection of the post-fired fin was limited to a visual (including microscopic) assessment of the fin surface condition (e.g., breakage, warping, melting, etc.) and a measurement of blade thickness, before vs. after firing, to determine the amount of erosion.

2.2 Dynamic Firing

Based on the static test results, several of the more "successful" alternative fin designs were selected for dynamic (normal launch) testing. An M735 105-mm KE projectile, shown entering free flight in Figure 2, was chosen as the test-bed projectile for carrying the candidate fin assembly downrange. The basis for choosing a 105-mm carrier projectile, as opposed to a 120-mm projectile, was economics: the M735 being less expensive than a comparable 120-mm round.

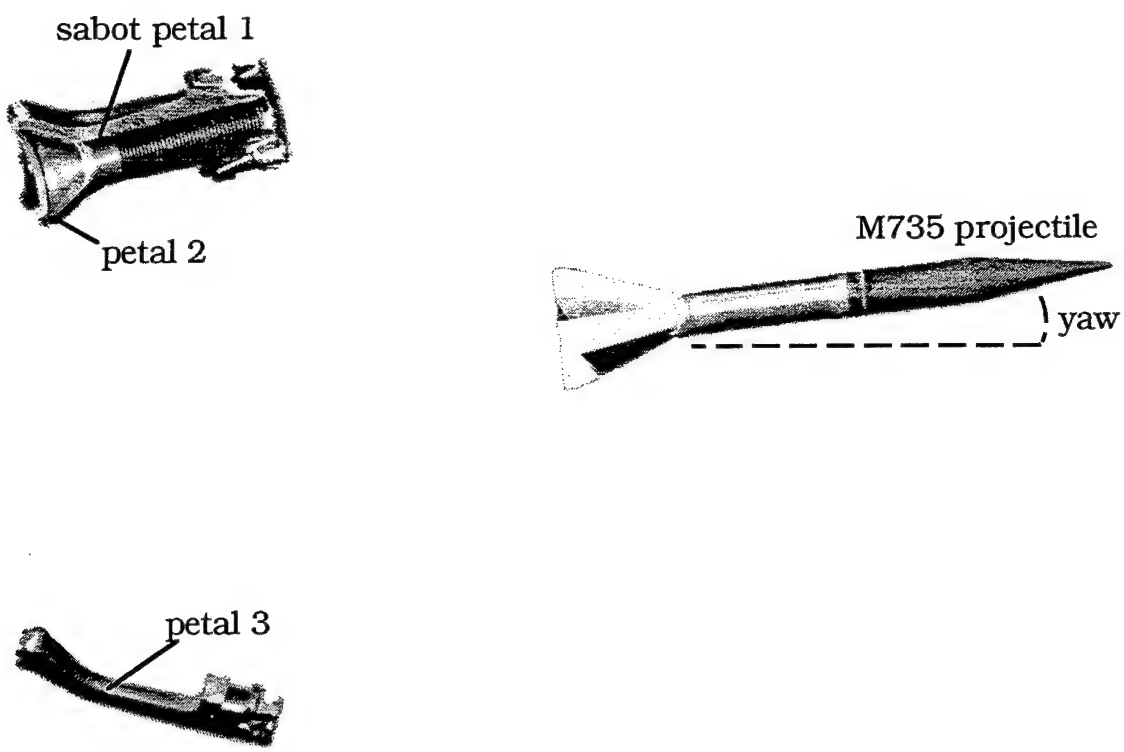


Figure 2. High-speed photograph of M735, just after sabot discard, ~9 m downrange from muzzle.

* Calculations were performed by Ronald Anderson, Propulsion and Fight Division, U.S. Army Research Laboratory, using the IBHVG2 interior balistics code.

Whereas the static test exposed the fins to extreme thermal conditions, this phase of the test subjected the fins to realistic mechanical loads, arising from launch acceleration and exposure to uneven muzzle exit pressure. Post-firing assessment of the candidate fin performance was based on muzzle exit radiographs, high-speed free-flight photographs (e.g., Figure 2), downrange yaw cards, and a target impact cloth. In some cases (when the fins failed), it was possible to obtain visual and microscopic (using a scanning electron microscope [SEM]) inspection of post-launched fin pieces found on the ground near the muzzle.

3. COMPOSITION AND DESIGN

3.1 Materials

In this investigation, all of the candidate fin assemblies (hub and blades) were composed either totally or substantially from organic materials. Fin fabrication was done at Los Alamos National Laboratory (LANL), under contract to what is now the Weapons and Materials Research Directorate (WMRD) of the Army Research Laboratory (ARL). In addition, LANL contributed some novel fin lay-up designs, including the injection molding of steel fins in a plastic hub.*

Three families of high-temperature plastics were examined: polyketones, polyimides, and phenolics. Fins were made from these resins with and without fiber fillers, which are added to change the strength and toughness of the overall plastic part. In general, there are advantages and disadvantages to fiber reinforcing of the fin. For example, a thin fin made from unfilled resin may be tough enough to absorb—without breaking (through flexing, bending, and stretching)—the short duration in-bore stresses created by propellant grain impacts, but it may flex beyond its elastic limit when subjected to the longer duration out-of-bore stresses created by uneven muzzle exit pressures. Adding chopped fibers to the injected resin to strengthen it against asymmetric muzzle exhaust flow will also increase its brittleness, in some cases, to the extent that in-bore propellant grain impacts may chip a thin fiber-

* Collin Sadler and Larry Ebaugh from LANL were responsible for the design and fabrication of this type of fin assembly.

filled blade. Filling the resin with longer fibers (e.g., by hand laying a broad cloth into the mold prior to processing) may increase the strength of a thin blade to the point where it no longer chips in bore or breaks out of bore, but with this solution, the simple, inexpensive process of injection molding the fin is no longer possible.

Since production cost is ultimately an important issue, we will henceforth separate the description of fin materials into those that can be injection-molded vs. those that require a hand lay-up step, followed by compression molding. In general, the injection-molded fins were made from either unfilled or short fiber-filled resins. The compression-molded fins were made from resins containing longer fibers that were actually part of a continuous fabric. (The design involving steel fins in a plastic hub was grouped with the injection-molded fins because the hand work was minimal prior to injection molding the hub.)

3.1.1 Short fiber-filled and unfilled plastics In this group, one polyimide and two types of polyketones were tested. In particular, the materials selected for injection molding were a polyetherimide (PEI) from General Electric Co., a polyetheretherketone (PEEK) from ICI, and a polyaryletherketone (PAEK) from BASF Corp. In addition to fabricating unfilled fin assemblies from these three thermoplastic materials, several PEI and PEEK fins were 40% filled with chopped carbon fibers to increase their strength, while some PAEK fins were 30% filled with short strands of E-glass for the same purpose. Lastly, a fin assembly was made by hand laying stainless steel (SS) fin blades into an injection mold. The SS fin hub was created by injecting a PAEK resin, with 30% short fiberglass filler, around fin tabs protruding from the root of the SS blades into the mold's fin hub cavity.

3.1.2 Long fiber-filled plastics Rather than laying a dry fabric into the mold and (hopefully) injecting resin through the fabric, it is common practice to use a fabric that is already preimpregnated with the resin (prepreg). The prepreged fabric is folded into the shape of the fin and then compression molded into the final part.*

* Note, the prepreged fabric will not harden until it is cured in the compression mold at an elevated temperature.

The materials selected for the compression molded fins were chosen from ICI's Fiberite line of ablative broad goods, used in the aerospace industry. In particular, the Fiberite materials that were tested included MX-4600 (a polyamide-modified phenolic resin with ~10-μm diameter E-glass fiber reinforcement), MX-2646 (a polyamide-modified phenolic resin with ~10-μm diameter silica fiber reinforcement), and MXBE-55 (an elastomeric-modified phenolic resin with hollow E-glass fiber reinforcement, ~10-μm diameter). All three Fiberite materials are thermosets. In general, thermoset materials are less flexible than thermoplastics because thermosets contain chemical bonds between polymers (crosslinks) that thermoplastics do not. These crosslinks prevent thermosets from melting and flowing the way thermoplastics can. Note, polyamide and elasomeric modifiers are added to the phenolic resin to increase flexibility/toughness of the composite fin assembly.

3.2 Dimensioning

In addition to differences in composition, strength can also be changed by varying the thickness of the fin blades. Two fin thicknesses were examined: 1.02 mm (0.040 in) and 1.52 mm (0.060 in). For comparison, the aluminum fin on the M735 KE projectile is 3.18 mm (0.125 in) thick at the base of the fin, where it joins to the hub, and 2.03 mm (0.080 in) thick at the tip of the fin. The rationale for selecting plastic fin thickness that were less than the standard aluminum fin was to begin with the thinnest conceivable fin (saving the most weight and aerodynamic drag), then, if necessary to increase fin strength, open up the mold (an irreversible step). However, due to unforeseen budget cutbacks in this project, the strategy of progressing from thin to thicker fins was never completed beyond the second mold iteration, 1.52 mm (0.060 in), which was still roughly one-half the typical aluminum fin thickness. The test matrix for materials and dimensions is summarized in Table 1.

Table 1. Test Matrix for Candidate Fin Assemblies

Injection Molded		Compression Molded
Unfilled Resin	Short Fiber-Filled Resin	Long Fiber Prepreg
PEI hub and blades (1.02 mm thick)	PEI, reinforced with 6.4-mm long carbon fibers in the hub and blades (1.02 mm thick)	MX-4600 (polyamide-modified phenolic), reinforced with a glass fiber broadcloth in hub and blades (1.52 mm thick)
PAEK hub and blades (1.02 and 1.52 mm thick)	PEEK, reinforced with 6.4-mm long carbon fibers in hub and blades (1.02 mm thick)	MX-2646 (polyamide-modified phenolic), reinforced with a silica fiber broadcloth in hub and blades (1.52 mm thick)
	PAEK, reinforced with 6.4-mm long glass fibers in hub and blades (1.02 and 1.52 mm thick)	MXBE-55 (elastomeric-modified phenolic), reinforced with a glass fiber broadcloth in hub and blades (1.52 mm thick)
	PAEK, reinforced with 6.4-mm long glass fibers in hub, and SS blades (1.52 mm thick)	

4. RESULTS

Before discussing each test case, a brief description of how plastics react to heat (Fire 1991) will aid in understanding the results. Plastics are essentially organic compounds consisting primarily of hydrogen, carbon, and in lesser quantity—oxygen, as well as trace amounts of various other elements that can bond covalently. Plastic is formed from the repeated covalent bonding of small molecular units (monomers) into long molecular chains (polymers); additives can be mixed with the

polymers to give the plastic a variety of special properties (e.g., fibers can be added for strength and elastomers can be added for toughness).

When a plastic is heated, the kinetic energy of the molecules can increase to the point where covalent bonds are broken, and simpler, smaller compounds are thus formed. As more heat is added, the breakdown continues until the compounds formed are light enough and active enough to exit the solid as a gas. The source of heat that vaporizes the solid plastic also heats the vapors emitted and thus breaks them down into free radicals of hydrogen, hydrocarbons, and other free radical components of the original polymer. (The heat-induced breaking of covalent bonds in the solid and in the vapor is referred to as pyrolysis.) It is the reaction of hydrogen and hydrocarbon free radicals with oxygen free radicals (pyrolized from the original plastic or from some other source in the fire) that releases heat—the heat of combustion—(some of which is in the form of light, creating a visible flame); this is the culminating step in the burning of plastic. If there is insufficient oxygen in the combustion mixture, the burning will be incomplete and will generate free carbon, leaving a telltale black residue on any unburned solid.

If the plastic is a so-called thermoplastic, heat can cause melting and flow before substantial pyrolysis can take place. Consequently, erosion can result from melt removal by "gas wash" over the surface. On the other hand, if the plastic is a thermoset material, it will not undergo melting prior to breaking down into vapor products. In this case, erosion is simply due to evaporation. However, if a solid component accompanies the hot gases, the plastic can also be eroded by chipping, especially for the less flexible thermoset plastics.

4.1 Static Test

In general, whether the fin is a thermoplastic or a thermoset, the in-bore heating time is so brief and the thermal conductivity so low that there is not sufficient time for an appreciable loss of plastic due to thermal ablation (melt removal or evaporation). Typically, 0.05–0.15 mm (0.002–0.006 in) of plastic was removed from exposed surfaces (e.g., hub and blades) during the combustion process in the static fin test. In

comparison, this could amount to 10–20% of the 1.52-mm blade thickness. However, there was one exception where thermal erosion of a compression molded fin was severe, exceeding 50%, as will be discussed.

Outcomes from the static fin test can be grouped as follows. The post-fired fins were either: (1) significantly eroded; (2) fractured (chipped); (3) warped; or (4) virtually undamaged, with the exception of a fairly uniform, but minor degree of ablation. Table 2 summarizes the results; the standard aluminum fin is included for comparison.

Table 2. Assessment of Static Firing Test Results

Eroded	Fractured	Warped	No Significant Damage
M735 aluminum fin (Figure 3)	MXBE-55 (Figure 4(b))	PEI, unfilled hub and blades, 1.02 mm thick (Figure 6)	MX-4600 (Figure 7)
MX-2646 (Figure 4(a))	PEI, fiber-filled hub and blades, 1.02 mm thick (Figure 5)	PAEK, fiber-filled hub and blades, 1.02 mm thick (like Figure 6)	PAEK, both unfilled and fiber-filled hub and blades, 1.52 mm thick (Figure 8)
	PEEK, fiber-filled hub and blades, 1.02 mm thick (like Figure 5)		PAEK, fiber-filled hub with SS blades

As Table 2 conveys, two of the statically tested fins incurred erosion damage, one of them being the standard aluminum fin. As reported by Bundy, Horst, and Robbins (1990), and shown in Figure 3, erosion of the aluminum fin is most severe at the leading edge, receding ~1.0 mm. A degree of nonuniformity can also be seen along the fin edge, varying from one blade to the next. The streak-like patterns extending downstream from the fin edge are deposits of Al_2O_3, resulting from the vaporization and subsequent oxidation of the aluminum substrate at the leading edge.

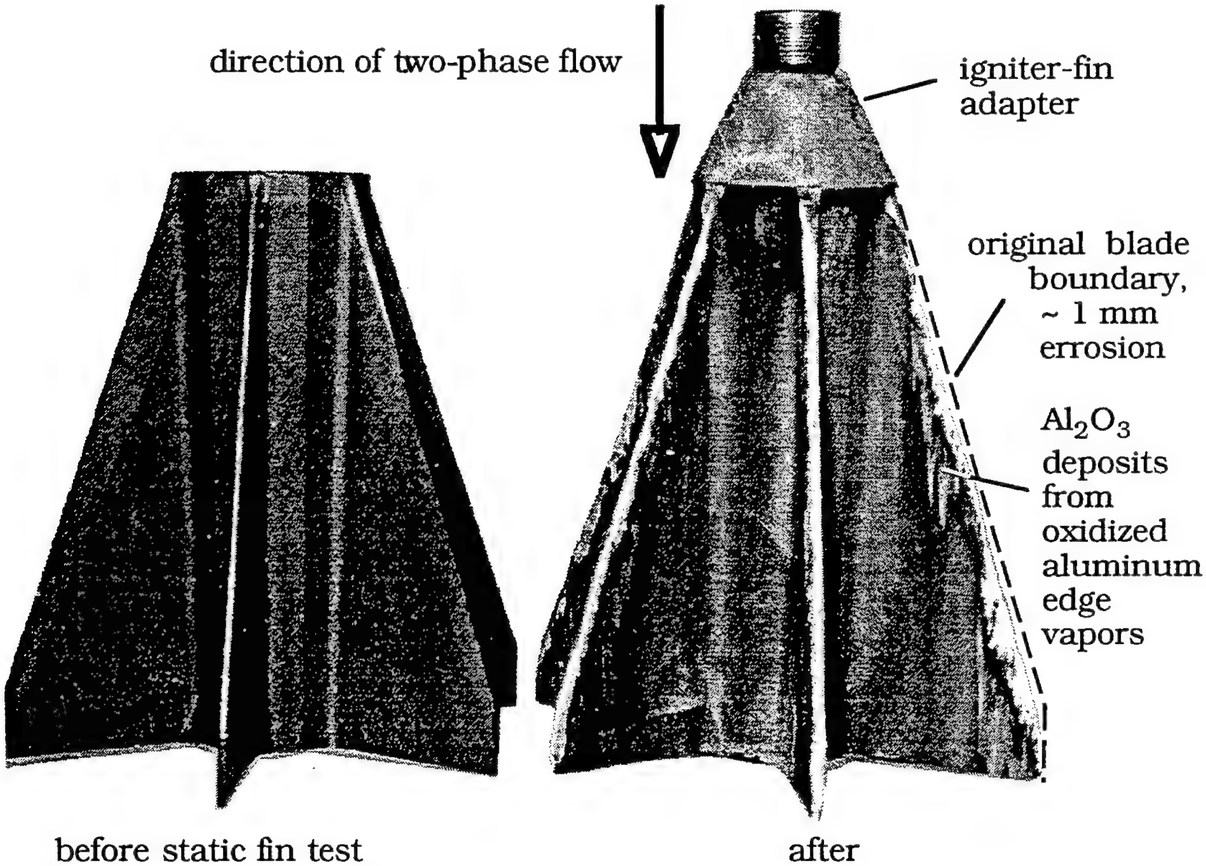


Figure 3. Static firing test result for the standard M735 aluminum fin.

Erosion of the compression-molded MX-2646 fin, Figure 4(a), was far worse than shown in Figure 3 for the aluminum fin.* Roughly 50% of the fin height was eroded (erosion also occurred in the width of the fin, perpendicular to the plane of view). It appears, note micrograph inset, that relatively large pieces of the silica crossweave were extricated by the combustion event, leaving voids in the blade surface and increasing exposure of the unreinforced phenolic to the two-phase flow. It is likely that the exposed phenolic matrix was simply chipped away by propellant grain impacts. Where silica fibers were exposed, there was evidence of fiber melting and coalescing at some of the fiber rod ends. In addition, small (< 1 μm in size) whisker-like extensions were found on the silica fibers; they are believed to be SiC crystals that were formed during the pyrolysis process.

* Note, in the static fin test for compression molded fins, three different thermoset resins were tested simultaneously by pinching the root of each blade into a multi-jawed steel collet, which was attached to the end of the igniter tube, Figure 1.

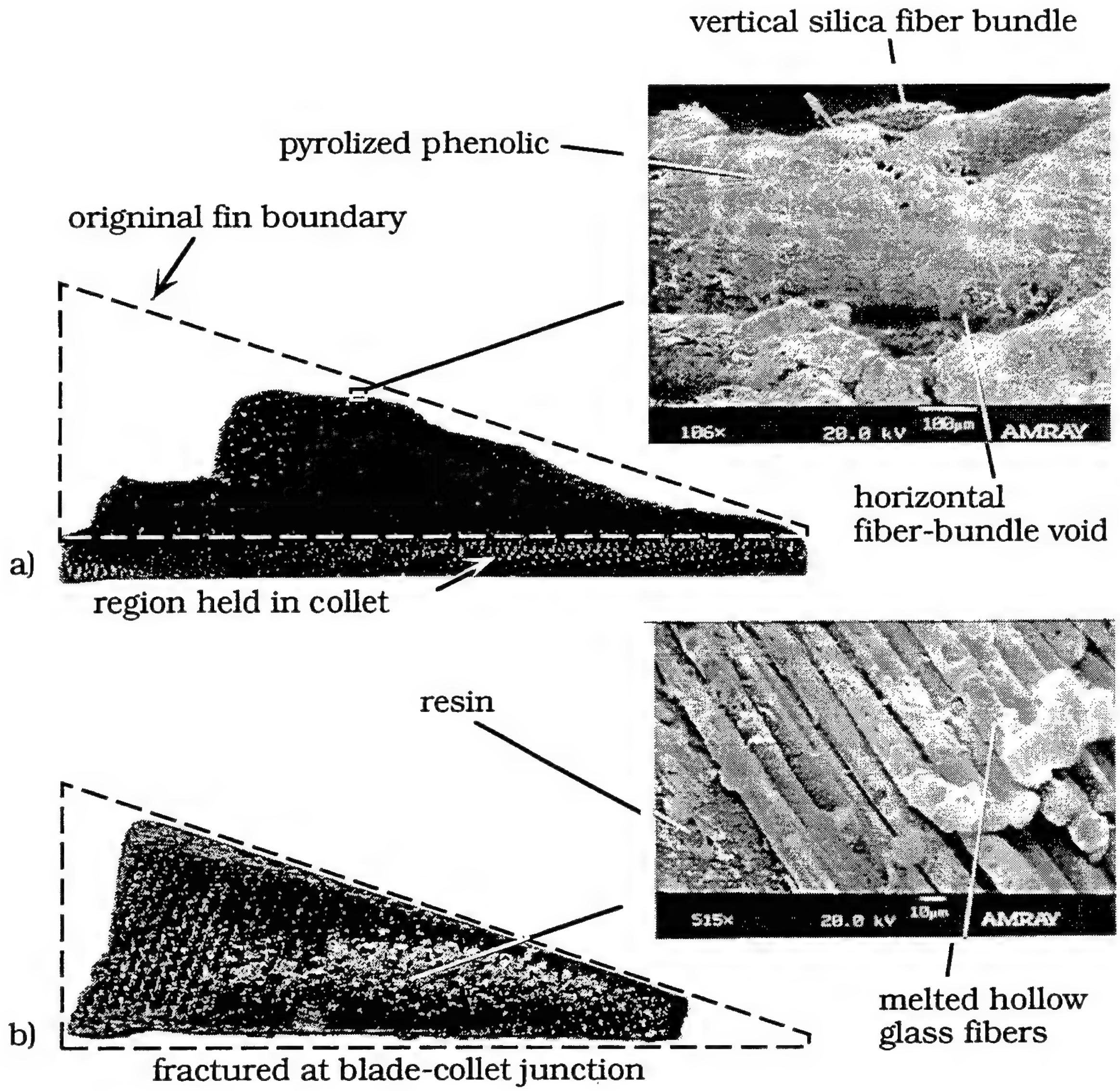


Figure 4. Static firing test results for (a) MX-2646 and (b) MXBE-55 compression-molded, fiber-filled, thermoset resins (1.52-mm blades).

The compression-molded MXBE-55 fin showed less erosion, Figure 4(b), than the MX-2646 fin (Figure 4(a)), but is probably unacceptable as a fin material since it fractured at the blade-collet junction. It is speculated that the hollow glass fibers did not add sufficient strength, nor the elastomer sufficient toughness, to prevent large-scale mechanical failure. Even though melted E-glass fibers were found on the blade surface, fiber bundles appeared to remain within the matrix, impeding erosion longer in this composite than in that of Figure 4(a). The fin width diminished by ~0.05 mm on each side, the equivalent of perhaps four to five layers of 10-µm fibers.

Some indication of the fin surface temperature can be gained from the test results noted thus far. On the conventional hardcoated aluminum fin (Figure 3), the vaporization of aluminum at the leading edge indicates a temperature near 2,300° C. For the compression-molded plastic fins, melting of the silica fibers indicates the surface temperature of the MX-2646 blade exceeded 1,900° C. Melting of E-glass in the MXBE-55 fin suggests the surface temperature was at least 1300° C. One might think that the thermoset plastics, being nonheat conductive compared to aluminum, would retain a higher surface temperature than aluminum. However, when the fiber reinforcement reaches its melting point (m.p.), the two-phase flow can extract heat by removing the molten fibers and surrounding pyrolyzed phenolic, thus limiting the surface temperature rise. It is speculated that a similar ablative heat removal process begins to occur with molten aluminum, but the near-surface exothermic oxidation of small ablating aluminum droplets quickly raises the blade surface temperature to its boiling point.

Another fin material that fractured in the static test was injection-molded PEI, with carbon fiber reinforcement in the hub and (1.02-mm thick) blades, Figure 5. The appearance of rather sharp-edged fin remnants, where the root of the blade joins the hub, implies that although PEI is a thermoplastic, the total loss of all fin blades is probably not due to melting for the most part. Rather, blade loss is most likely caused by chipping of a thermally eroded (thinned) fin. In fact, thickness measurements of the remaining blade fragments revealed that roughly 0.15 mm of material was removed from each side of the blade. This surface regression is roughly three times the level noted for the compression molded fins, and it leaves the remaining ~ 0.7-mm thick fin susceptible to chipping.

Finally, as recorded in Table 2, the 1.02-mm injection-molded PEEK fins, with carbon fiber filler, also fractured in the static test. The reduction in blade thickness was again near 0.15 mm per side, and the fin loss was complete, like that shown in Figure 5.

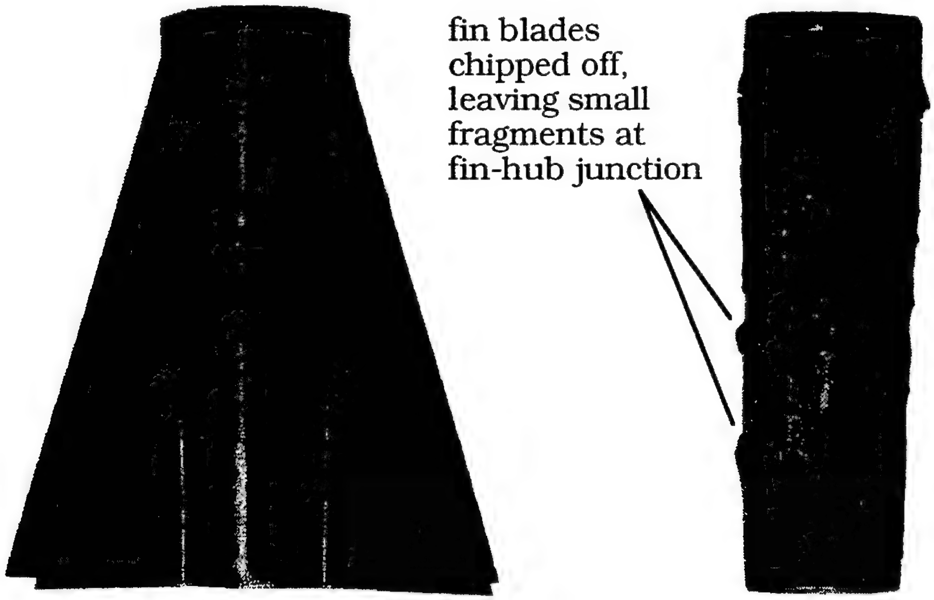


Figure 5. Static firing test result for PEI resin with 40% carbon fiber filler (1.02-mm blades).

Even though the loss of thermoplastic material was about the same for the unfilled PEI as for the fiber-filled PEI, ~ 0.15 mm per side, the unfilled resin is tough enough to resist fracture from propellant grain impacts, Figure 6. However, the fin blades were left warped by the static heating event. Apparently, the remaining blade material, ~ 0.7 mm thick, absorbed enough heat to be stressed beyond its elastic limit by thermal softening. Likewise, a similar level of heating and erosion left the injection-molded, fiber-filled, 1.02-mm PAEK fins warped, looking like those of Figure 6.

In general, the fiber-filled or unfilled thermoplastic resins, PEI, PEEK, and PAEK, which have melting points near 350° C, all showed a loss of blade thickness that was two to three times higher than the MXBE-55 thermoset resin with E-glass fibers (m.p. 1316° C). The apparent inverse correlation between depth of erosion and m.p. of the resin, or fiber, may imply that the onset of ablation is determined by the lowest m.p. in the composite, whether that is in the matrix or in the fiber.

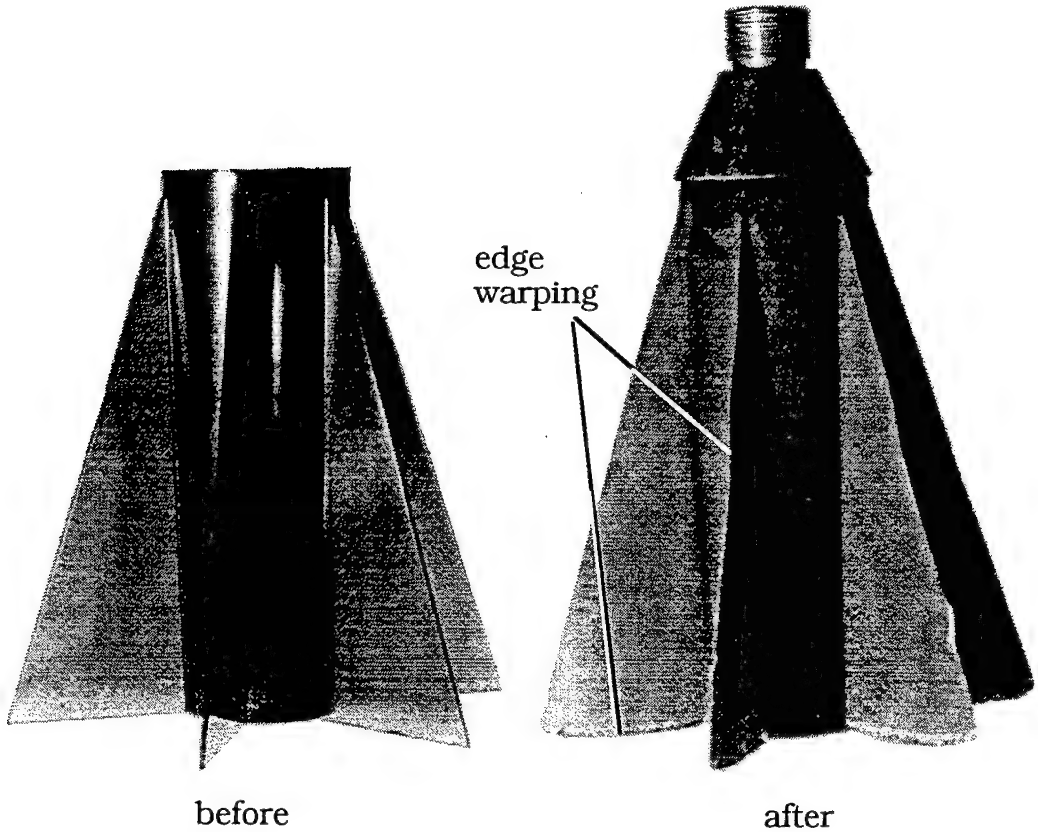


Figure 6. Static firing test result for unfilled PEI resin (1.02-mm blades).

There were four fins materials that survived the static heating test with virtually no damage. They were the MX-4600 compression-molded blade (1.52 mm thick), the unfilled and short fiber-filled PAEK injection molded fin (1.52 mm thick), and, as expected, the 1.52-mm SS fins in a fiber-filled PAEK hub.

Figure 7 shows the post-heated MX-4600 blade. The SEM micrograph reveals melted and coalesced E-glass fibers separating from the underlying reinforcement. Thickness measurements indicate that ~ 0.07 mm of the glass and resin matrix was eroded from each side. Unlike the MXBE-55 fin, the 10-μm glass fibers in the MX-4600 blade were solid, not hollow; this, in conjunction with a difference in modifiers, increased the strength of the blade, preventing fin damage like that which occurred in Figure 4(b). It is worth noting that the MX-2646 fin has the same resin and modifier as MX-4600—but different fibers (silica vs. E-glass)—yet, the MX-2646 fin failed catastrophically (Figure 4(a) in comparison to Figure 7).

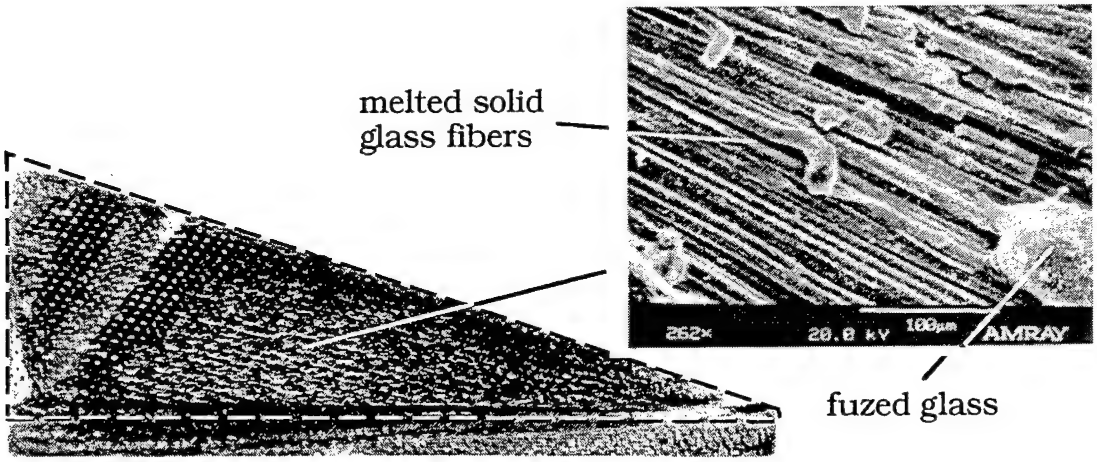


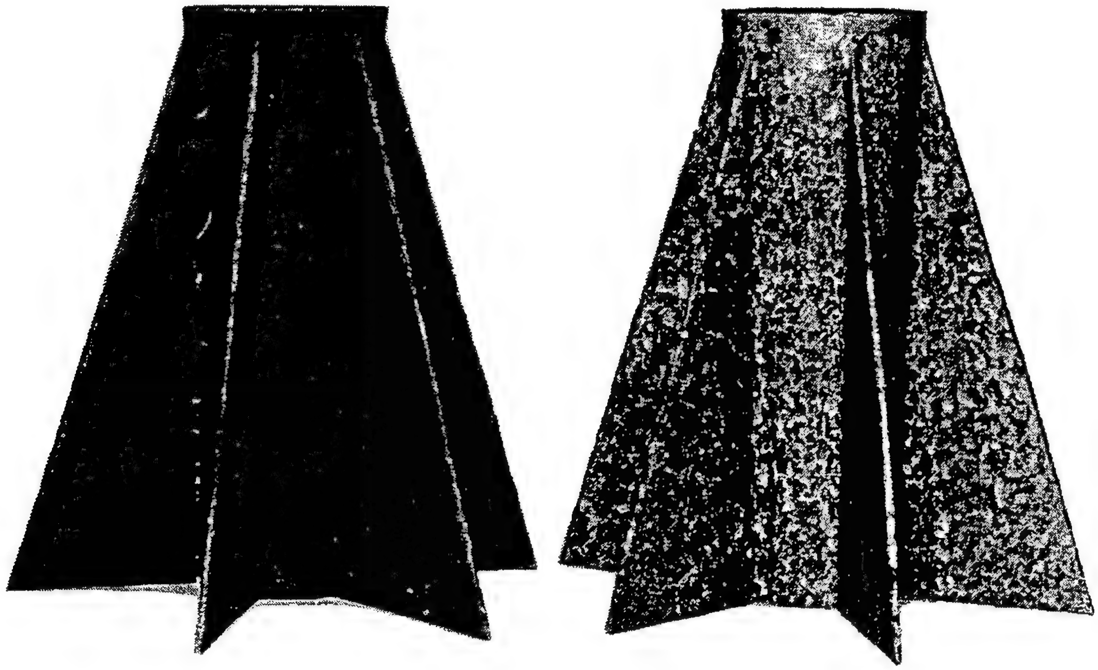
Figure 7. Static firing test result for MX-4600 compression-molded, fiber-filled, thermoset resin (1.52-mm blades).

Increasing the blade thickness of the thermoplastic PAEK resin to 1.52 mm substantially improved the results (Figures 8(a) and (b) [with and without fiber filler, respectively] compared with Figure 6). As shown, there was virtually no damage to either fin assembly after the static heating test. Once again, ~ 0.15 mm of composite material was thermally eroded from each side of the blades in Figure 8, leaving a fin thickness of ~ 1.2 mm. Apparently, the added 0.5 mm of fin width prevented thermal softening from warping the blades as it did in Figure 6. Even though the amount of material removed from each blade was about the same, there appears to be a slightly heavier layer of (darker colored) carbonaceous char (indicating less available oxygen for burning) on the fin with E-glass filler (Figure 8(a)) compared to the fin without filler (Figure 8(b)).

The only candidate fin design yet to be discussed from Table 2 is the SS blades in the fiber-reinforced PAEK hub. As expected, the SS blades were undamaged by the two-phase flow, and the 0.15 mm recession of the PAEK hub radius was inconsequential.

Of the four fin materials that were virtually undamaged by the static firing test, the lightest was the unfilled PEAK fin assembly (hub and blades) at 70 g. The filled PEAK was slightly heavier, 75 g, followed by the MX-4600, 110 g. The SS blades in a fiber-filled PEAK hub were

the heaviest of all the designs, at 215 g, heavier than the conventional aluminum M735 fin assembly, 175 g.



a) b)

Figure 8. Static firing test result for (a) PAEK resin reinforced with 30% E-glass fibers and (b) unfilled PAEK resin (both had 1.52-mm-thick blades).

4.2 Dynamic Test

If the fin failed thermally or mechanically in the static fin test, that design was not among those included in the dynamic test. Hence, only the fourth column of Table 2 was examined in this phase.

It has been noted that the dynamic test phase is not as thermally challenging to the candidate fin assemblies as the static fin test. Thus, it was not expected, nor did it occur, that any of the fins that survived the static test failed the dynamic test due to temperature-related damage. On the other hand, the dynamic test exposed the fins for the first time to realistic launch accelerations and uneven muzzle exit pressures; hence, new forces were present that could cause the fins to fail mechanically. Table 3 summarizes the results.

Table 3. Assessment of Dynamic Firing Test Results

Catastrophic Failure	Borderline Failure	Occasional Success
Compression-molded MX-4600 hub and blades	Injection-molded, fiber filled PAEK hub and blades	Injection-molded, unfilled PAEK hub and blades
		Injection-molded, fiber-filled PAEK hub with SS blades

As indicated by the column headings in Table 3, there were no unequivocal successes among the fin designs tried. However, there were occasions when individual fin assemblies flew downrange with little or no apparent damage. Before discussing the occasional successes, the unsuccessful designs are discussed.

One of the most complete failures in the dynamic firing test was the compression-molded MX-4600 fin assembly, Figure 9. In spite of the static firing success of this polyamide-modified phenolic, with glass fiber broad cloth reinforcement, the broad cloth lay-up delaminated and was shred into hundreds of tiny pieces after it left the muzzle. One explanation for the failure is that high-pressure propellant gases entered into the interstitial cavities and voids between the fibers and resin while the assembly remained in-bore, but did not escape fast enough, once out-of-bore, to avoid exploding the part. Evidence that the failure occurred out of bore was based on the fact that only a small fraction of the fragments showed signs of in-bore exposure to high temperatures (i.e., melted or charred surface fibers).

In Figure 9 the rod is flying downrange with a yaw angle of ~ 5° at 5–6 m from the muzzle. Although this is not an unusually large yaw angle at this location (e.g., it is similar in size to that shown in Figure 2 for the standard M735), a fraction of a second later, at 41 m from the muzzle, the yaw angle has increased to at least 45°. This unacceptably high angle, shows by counter example, how important fins are to stabilizing the rod and keeping the yaw angle small.

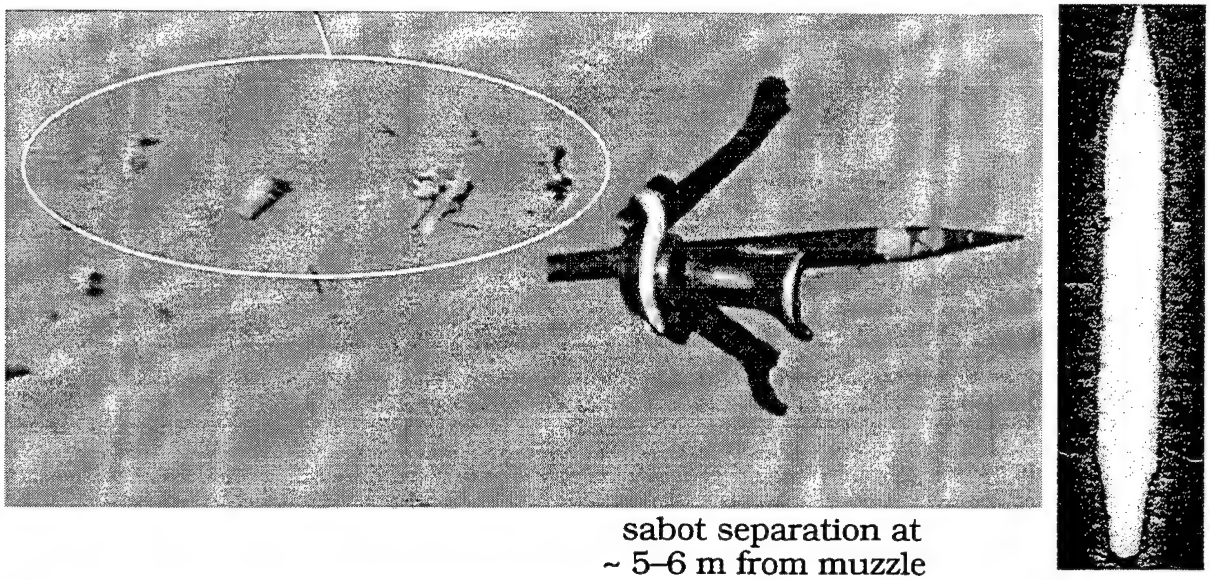


Figure 9. (a) High-speed downrange photograph, and (b) downrange yaw card imprint of M735 rod launched with MX-4600 fins

The fin assembly fabricated by injection molding PAEK, containing 30% short glass fibers, was a borderline failure because in no cases did it enter free flight without some fin damage, like that shown in Figure 10. It is speculated that if the KE rod has some nonzero angle of attack with respect to the reverse muzzle exhaust flow, which is almost certain to be the case, then the dynamic pressure from this flow can bend the fin blades beyond their yield point. This would explain the large number of broken fin tips found on the ground downrange from the muzzle, one of which is shown in Figure 10. The SEM micrograph of the fin tip surface indicates that the blade surface is softened by the in-bore transient heating. It appears that when propellant grain fragments hit this soft layer they leave crater-like imprints. Flat-bottomed craters imply that the plastic is not thermally softened, to the point of being inelastic, below a certain depth, in this case ~ 0.03 mm. Thickness measurements of the fin fragments revealed that ~ 0.05 mm of surface material was eroded from each side of the blades, this is about one-third the level of erosion that occurred in the static firing test.

Even though the loss of fin surface area was not complete in Figure 10, it was significant to the extent that it would be unacceptable in terms of the effect it has on destabilizing the round, which is borne out by the high yaw angle of ~ 15° near 30 m from the muzzle.

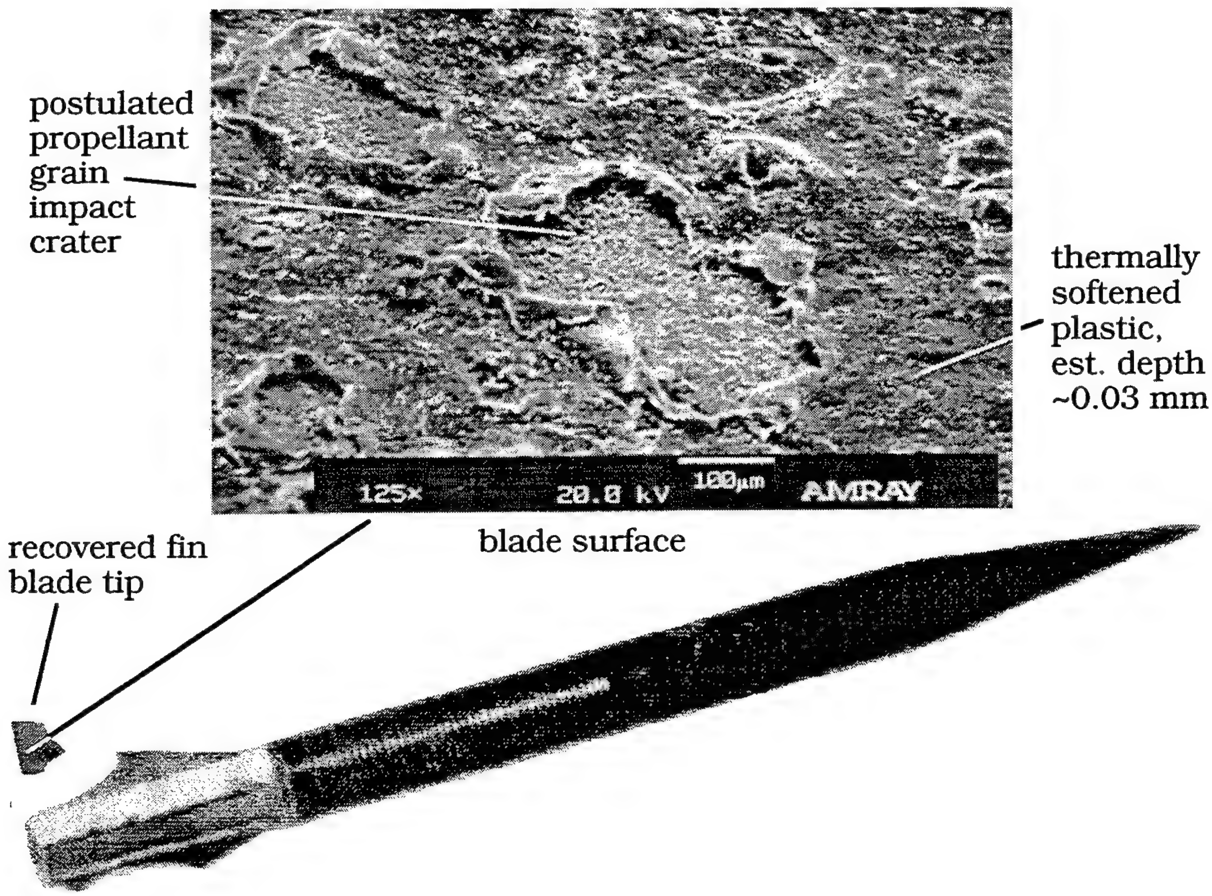


Figure 10. High-speed downrange photograph (~ 30 m from the muzzle) of an M735 rod launched with a fiber-filled PAEK fin assembly.

The SS-plastic fin design was occasionally successful, but when it failed, e.g., Figure 11, the loss of blades was as complete as that of Figure 9. The appearance of curled and twisted SS blades in Figure 11 implies that the reverse muzzle exhaust flow impinged on the blades from an oblique angle (note, the yaw angle of the rod in Figure 11 was about 3°), forcing the blade tips to curl over and eventually twisting them out of the plastic fin hub.

The tracer cavity plug, shown in Figure 11, is utilized as a precaution to prevent in-bore gases from filling this cavity and not escaping fast enough, after muzzle exit, to avoid exploding the fin hub.

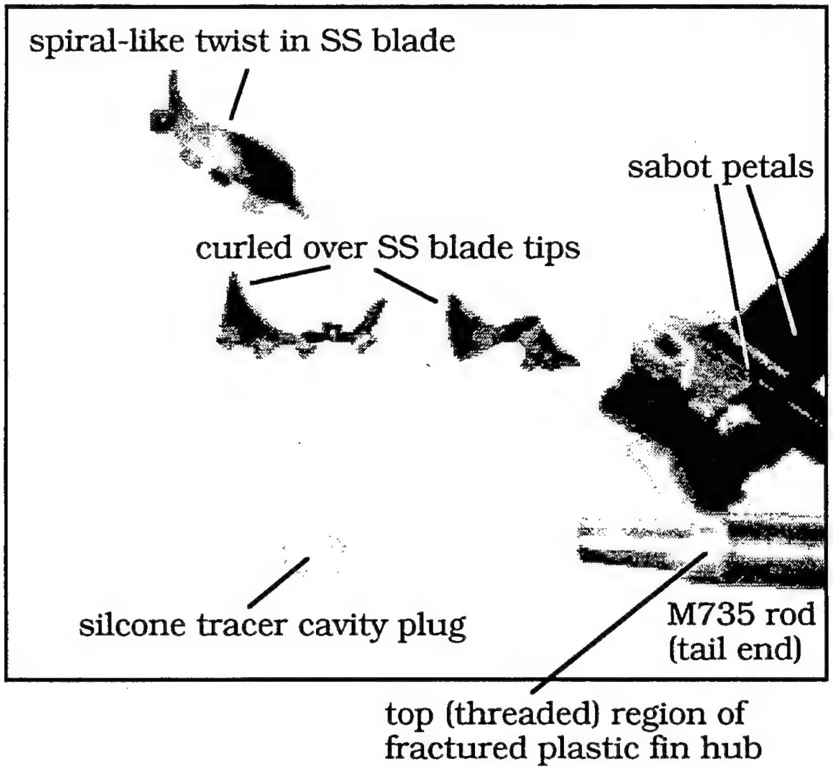


Figure 11. Downrange photograph (edited of debris for clarity, using an image scanner) of an M735 rod launched with SS fins molded into a fiber-filled PAEK hub.

The unfilled PAEK fins gave the most promising results. Out of two fin assemblies tested, high-speed photographs and yaw card imprints showed one assembly lost two of six fin tips due to fracture, with the remaining four tips exhibiting extreme flexure. However, the other PAEK fin assembly flew downrange essentially undamaged, as shown in Figure 12. The yaw cards, at 41 m and 53 m from the muzzle, show that all fins are full span and none are chipped. There appears to be a slight flexing of some blades as indicated by the small curvature in the yaw card silhouette. (It is presumed that the blades are flexing because no permanent warping was observed in the more intense thermal environment of static firing.)

It has been speculated that the initial yaw angle relative to the reverse muzzle exhaust flow contributes to the loss of fins, due to bending of the blades by asymmetric dynamic pressure loads. Unlike Figures 2, 9, and 11, the yaw angle at ~ 7 m from the muzzle in Figure 12 is small, < 1°, and was probably small at muzzle exit. This

would suggest that asymmetric dynamic pressure loads were probably small at muzzle exit, which could help explain why there was not only no fin chipping, but very little fin flexing. Furthermore, the continued low yaw angles at 41 m and 53 m from the muzzle (indicated by the near circular yaw card impacts) demonstrates that the fin is serving to maintain flight stability of the rod.

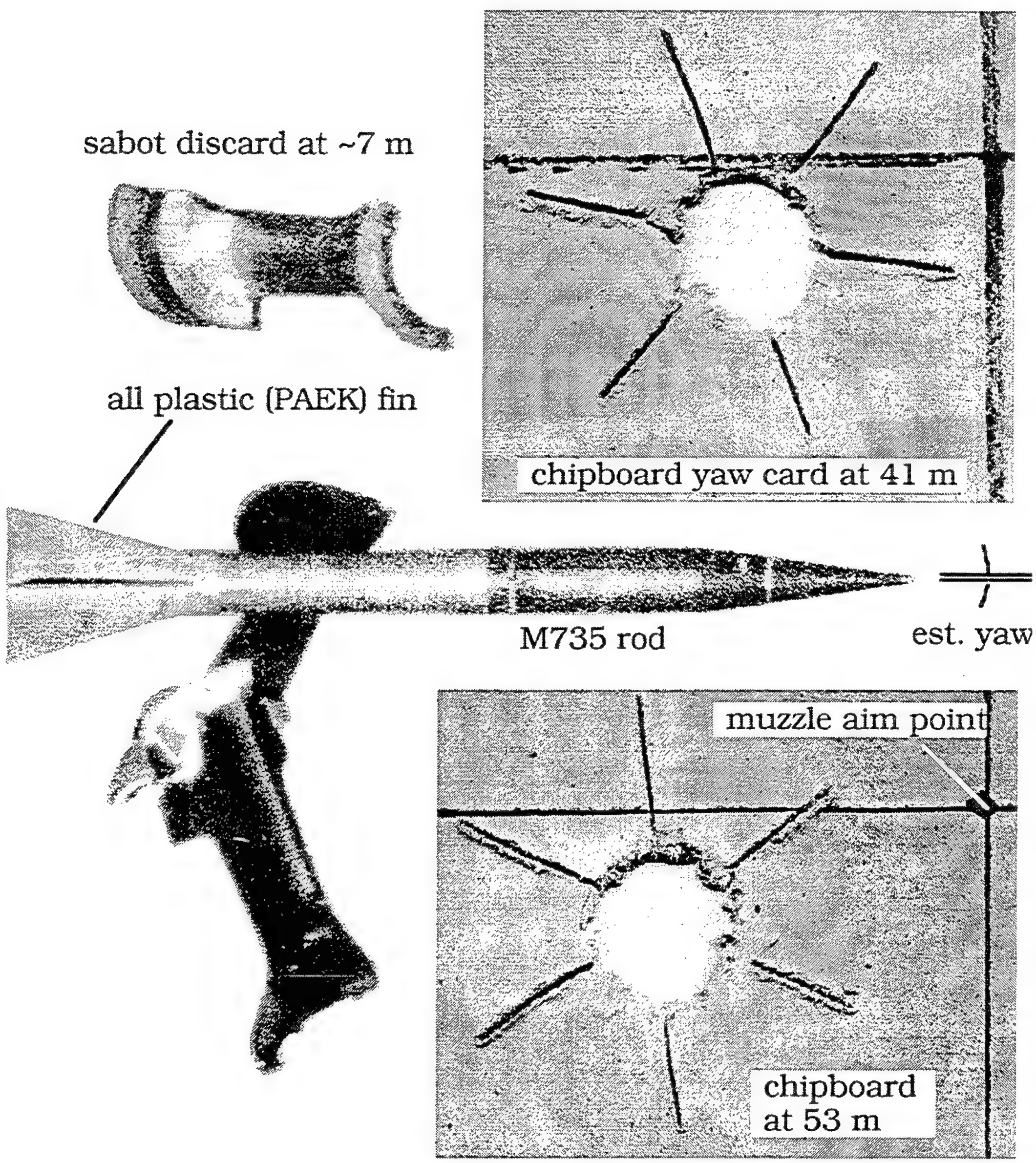


Figure 12. High-speed photograph of an all-plastic (PAEK) fin assembly on a carrier M735 long rod penetrator.

5. CONCLUSIONS AND RECOMMENDATIONS

This report documents a multiyear study of plastic fins for use on long rod KE penetrators. An M735, a 105-mm round with a muzzle exit velocity of ~ 1600 m/s, was chosen as the carrier projectile for test comparisons. Several types of plastics were evaluated, from specialized compression-molded broad clothes, preimpregnated with thermoset resins (like those used in the aerospace industry), to more general purpose injection-molded engineering-type thermoplastics (such as PEEK).

The long-range plan of the program was to start with thin molded fins, roughly one-third the blade thickness of the standard aluminum fin, then open up the mold (an irreversible step) if necessary, to increase the blade thickness (strength). However, lack of continuing funds halted the program at the second fin thickness iteration, which was still only one-half the standard aluminum fin thickness. Nevertheless, a great deal was learned about the use of plastics for this application.

Nine candidate fin materials were chosen for testing. Of these nine, only four performed better than aluminum in resisting in-bore damage from the two-phase propellant flow (as determined in static fire testing). These four then underwent further testing by launching them on the carrier M735 rod. Of the four, two were occasionally successful in stabilizing the rod, with no appreciable thermal erosion or mechanical damage (bent or chipped fins).

One of the two occasionally successful fins had SS blades in a plastic hub. However, further development of this design is not recommended since there is little room for substantial improvement in the design without increasing the fin weight, which is already heavier than the baseline (M735) aluminum fin.

On the other hand, the other occasionally successful design, an all-plastic fin assembly (injection-molded using an unfilled thermoplastic resin—PAEK from BASF Corp.) has considerable latitude for improvement without exceeding the drag and weight penalties of the standard aluminum fin. For example, it is believed that going from the

current 1.52 mm straight-cut PAEK fin to a 2–3 mm tapered-cut (from tip to root) PAEK fin, would provide the necessary margin of safety to ensure a damage-free transition to free flight. Since such a shape is roughly the same as the baseline aluminum fin there would not be any benefit from reduced drag, but the PAEK fin would offer a weight savings: weighting only 50–60% as much as its aluminum counterpart. (A fin weight reduction is advantage to improving flight stability because it moves the center of gravity forward, which increases the stabilizing moment.) Most importantly, the test results showed that thermal erosion for such a plastic fin would be far less—and more uniform—than for a comparable aluminum fin. For example, from the static firing test, it was shown that the PAEK fin had a uniform erosion of ~ 0.15 mm, whereas, for the aluminum fin, the leading edge regression was ~ 1 mm, and it varied from blade to blade. Nonuniform erosion creates the adverse effect of increasing ammunition dispersion.

In general, this study proved that a thin (one-half as thick as the standard 2–3-mm aluminum fin), lightweight (40% as heavy as the standard 175-g fin) all-plastic (PAEK) fin assembly can stabilize a long rod (M735) KE penetrator with virtually no in-bore thermal erosion (~ 0.05 mm surface regression). However, to prevent out-of-bore mechanical fin damage (bent or chipped blades) it appears that the rod must exit the muzzle at small yaw angles. To enlarge the tolerance to muzzle exit angles requires thickening the PAEK fin blade (as discussed above). Hence, the critical factor in plastic fin design is not thermal erosion, as one might expect, but rather, it is the ability to flex without breaking in the reverse muzzle exhaust flow. This would indicate that if other polymers are considered for fin applications in the future, the sought after characteristics would be for more flexibility, elasticity, or rubber-like qualities than PAEK.

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13. ABSTRACT *(Maximum 200 words)*

Most conventional sub-caliber long rod penetrators maintain flight stability by using near-full-caliber hardcoated aluminum fins that extend from the base end of the projectile. Prior to launch, these fins are buried within the propellant bed of the ammunition cartridge case. During launch, the fins are subjected to high propellant gas temperature and pressure, as well as propellant grain impacts. This thermally abrasive in-bore environment can remove pieces of the fin's hardcoat, thus exposing the aluminum substrate to temperatures far beyond its melting point. Thermal erosion of the fin degrades projectile stability and accuracy. Thus, the U.S. Army is exploring more effective thermal coatings and/or substitute fin materials to replace hardcoated aluminum. The use of plastics is one alternative. This report will document some of the successes and failures of plastic fin assemblies on kinetic energy (KE) penetrators. For example, it was found that fins made from some plastics incur less in-bore thermal damage than hardcoated aluminum. On the other hand, it appears that plastic fins, at least relatively thin plastic fins, are susceptible to mechanical failure out of bore if they traverse the reverse muzzle gas flow at all but small yaw angles. Nonetheless, there appears to be design latitude for a plastic fin assembly that would be lighter in weight and more erosion resistant than the current hardcoated aluminum fin.

14. SUBJECT TERMS

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